Structural Concepts and Mechanics Issues for Ultra-Large Optical Systems

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Introduction

The desire to build ultra-large (i.e., larger than 10 meter aperture) optical systems on-orbit is certainly not new to NASA. Many programs in the past have studied various concepts for such systems, and a substantial amount of technology-development funding has been invested in the interest of making such systems feasible. Unfortunately, despite these investments, no practical concepts for ultra-large optical systems have yet been developed.

However, recent research has begun to shed light on one of the most potentially problematic issues facing ultra-large optical systems - microdynamic instabilities in mechanically jointed optical metering structures (e.g., distributed truss structures for supporting segmented primary mirrors and secondary mirror support structures). Recent tests have shown that mechanically jointed optical metering structures exhibit microdynamic instabilities at levels of motion comparable to the wavelength of visible light (i.e., less than a micron). These instabilities can result from inherent, non-classical behavior of mechanical joints and materials, and are first order influences on the design of deployed optical systems. Fortunately though, substantial advancements have been made in understanding these undesirable response phenomena, and practical design principles have been established to minimize their effects. These advancements, coupled with other recent advancements in structures and materials technology, warrant a revisit of ultra-large optical systems.

The purposes of this paper are to: 1) review briefly the history of concept development of ultra-large optical systems; 2) review briefly recent research on microdynamics of deployed optical systems; and 3) discuss some of the technical challenges that remain before ultra-large deployed optical systems can become practical.

Past and Future Structural Concepts for Ultra-Large Optical Systems

Since the early 1960's, NASA has sponsored numerous technology-development initiatives to study the feasibility of ultra-large (i.e., larger than 10 meter aperture) optical instrument systems (ref. 1). The most recent of these initiatives, the Large Deployable Reflector (LDR) Program (e.g. refs. 2 through 4), was started in the mid 80's and continued through the early 90's. The LDR Program focused on the development of a 20-m-class, far-infrared optical telescope and considered many system architectural issues such as mirror fabrication concepts and on-orbit construction techniques (see Fig. 1).

Although the surface precision requirement for LDR was relatively low (i.e., tens of microns, RMS), a membrane mirror was considered to be technically infeasible, so all LDR concepts incorporated a segmented, hard-surface mirror. In fact, substantial LDR technology-development funding went into the development of low-areal-density, composite mirror panels. Since the LDR Program, some advancements have been made in membrane-mirror technology. However, it is still important to maintain a realistic view of the feasibility of membrane mirrors for future ultra-large optical systems. It is probably impossible to fabricate membrane mirrors (especially ultra-large membrane mirrors) with surface figures better than

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tens or hundreds of microns. Therefore applying membrane mirrors to future ultra-large optical systems would require extensive application of active shape control and/or image correction. Although advancements have been made in both of these technologies since the LDR Program, no viable, actively controlled or corrected membrane mirrors have been demonstrated to date.

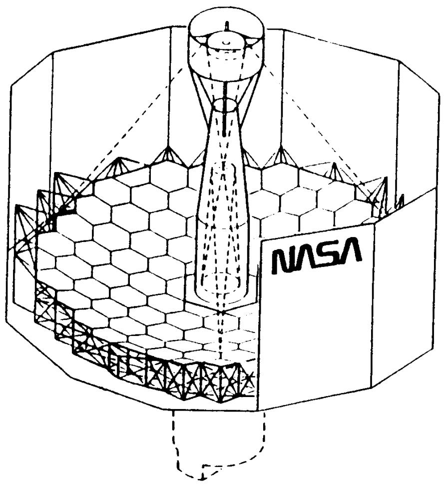


Fig. 1 20-m-diameter LDR concept.

In addition to considering the type of mirror (i.e., segmented, hard-surface mirrors versus membrane mirrors) for future ultra-large aperture instrument systems, it is important to reconsider all methods of on-orbit construction of the mirrors. Recent research efforts have been focused on mechanical deployment as the preferred method of on-orbit construction of segmented, hard-surface mirrors. This focus on mechanical deployment is consistent with the relatively small deployed aperture sizes and relatively simple deployment schemes currently envisioned for the first generation of deployable optical science instruments (e.g., the Next Generation Space Telescope, NGST as shown in Fig. 2). However, as aperture diameters increase to greater than 10m, and segmenting patterns and stowage geometries become more complex (e.g., highly segmented LDR concept shown in Fig. 1), other methods of construction such as automated (i.e., robotic) and manual (i.e., astronaut-aided) assembly should be considered again as well.

During the LDR program, all three methods for constructing truss-supported, segmented, hard-surface reflectors were considered: mechanical deployment, automated assembly by robots, and manual assembly by astronauts. The key discriminators used to compare these construction methods were reliability and cost of on-orbit construction, and passive precision and predictability of the completed structure.

At the time of the LDR program there was a lack of test data in the open literature to verify that high-precision deployment mechanisms could be developed with predictable micron-level structural behavior. Without such mechanisms, it was feared that deployable reflectors would only achieve relatively low surface precision without active control. In addition, the relatively complex deployment kinematics required to package the 20-m-diameter LDR for launch caused concern that deployment reliability might not be easily assured.

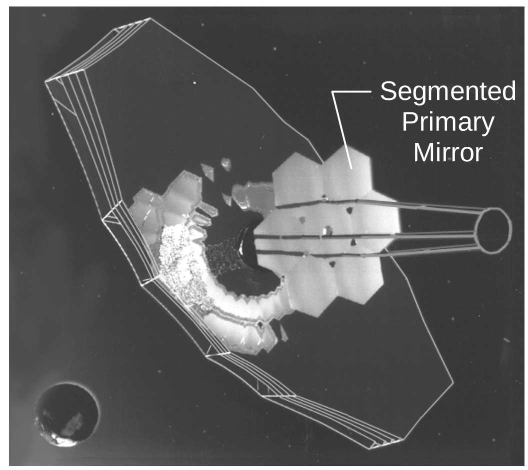


Fig. 2 NGST concept showing a relatively simple primary mirror segmenting pattern.

On the other hand, ground tests demonstrated that erectable truss joints, developed by NASA, exhibited a highly linear load-deflection response and the static and dynamic behavior of trusses incorporating the joints was seen to be linear down to about 50 microns of motion (ref. 5). Furthermore, relatively rapid, low-cost fabrication procedures were developed for high-precision, erectable metering structures, and the LDR program ultimately baselined an erectable metering structure as the highest-precision structural concept available at that time. In addition, detailed structural performance studies were conducted from which explicit structural sizing equations were developed (e.g., ref. 6).

Numerous construction studies were performed at this time that considered using the International Space Station for either robotic or astronaut-aided construction of large reflectors like LDR (e.g., ref. 2 and Fig. 3). Detailed ground-based test programs were also performed to investigate both robotic and astronaut-aided assembly techniques. While tests of a ground-based robotic construction system (ref. 7) showed that a reliable, low-cost, flight system would take many years of additional research to develop, simulated EVA assembly tests (ref. 8 and Fig. 4) indicated that astronauts could efficiently and reliably assemble precision reflectors using existing EVA technology.

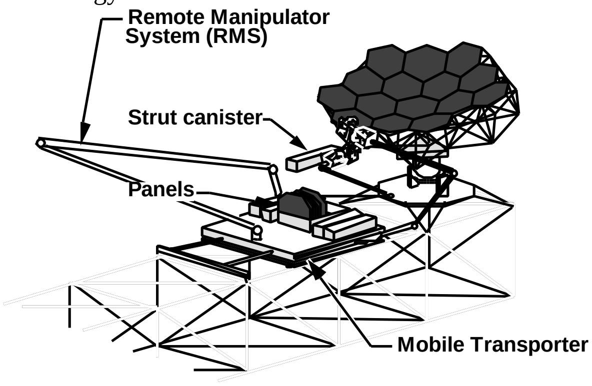


Fig. 3 ISS-based construction of LDR.

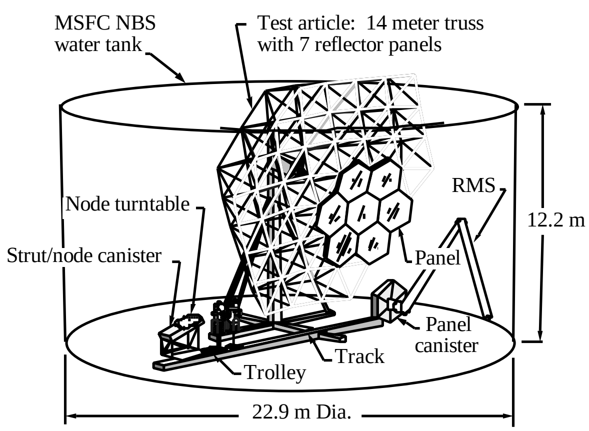


Fig. 4 Schematic of 1992 underwater EVA assembly test of a 15-m precision reflector.

Regardless of whether future ultra-large optical systems are mechanically deployed or robotically or manually assembled, the metering structures for these systems will likely include many mechanical joints (i.e., hinges and/or latches, ref. 9). Recent research on mechanically jointed, precision deployable structures has shown that nonlinear response to loading in the joints affects the dimensional precision of the structure, and, hence, affects optical alignment of the instrument components attached to the structure (ref. 10).

Effects of Microdynamics on the Design of Ultra-Large Optical Systems

The word "microdynamics" is ordinarily associated with a broad class of nonlinear structural dynamic phenomena with response magnitudes at or below the microstrain level (i.e., 10^{-6} times a characteristic dimension of the structure). Microdynamics have been observed in numerous ground and on-orbit tests of 2 to 3-m-class precision deployable structures, and will most certainly exist in future ultra-large-aperture deployable or erectable optical structures. By definition, microdynamics are nonlinear and difficult to model analytically, and in some cases, microdynamics can present challenges to active control systems.

While our understanding and observations of microdynamic nonlinearities are incomplete, an important microdynamic response phenomenon has been identified, which might complicate the design of active control systems (ref. 11). This phenomenon, referred to as "microlurch," is a residual change in the shape of a mechanically jointed structure which occurs after a dynamic disturbance. Current models predict that microlurch is caused by a sudden release of strain energy that is built up due to frictional interactions within the joints and latches of a deployed structure.

To complicate the implementation of high-bandwidth active shape control systems, the sudden release of strain energy during a microlurch has the potential to excite high frequency structural dynamics which can fall outside the practical bandwidth of an active control system. It is perhaps this aspect of microdynamics that is most troubling to the developer of active shape-control systems. For example, future ultra-large space-based interferometers will require nanometer stability up to at least 1,000 Hz, but current technology in active delay-line controllers have bandwidth limitations of several hundred Hertz. If a microlurch occurs during the formation of an image or during an astrometric measurement, it is likely that the instrument would need to be realigned and the measurement begun again. Persistent events of this type would directly limit mission science data.

The design of any lightweight, precision, mechanically jointed structure must involve a trade between passive precision and active control. For small-aperture systems, the active control can probably be incorporated relatively efficiently and economically. However, for ultra-large-aperture optical systems, the very size of the systems, and the large number of mechanisms involved, indicates that microdynamics could become an even greater problem to actively correct. Incorporation of active control can become costly and complex if the problem is approached in a “brute force” fashion, but there is promise that excessive cost can be avoided by following a systematic approach to the development of active control systems.

Before explaining the issues that must be considered in developing an efficient active-control system, it is useful to define explicitly two aspects to the dimensional precision of a deployed (or erected) structure:

1. **Deployment Precision**: Error in the final deployed shape of a structure as compared to its shape predicted from ground measurements.

2. **Post-Deployment Stability**: Variation in the deployed shape of a structure in response to on-orbit thermal and mechanical loads.

To minimize the cost and complexity of active control systems, it is prudent to characterize carefully the passive deployment precision and post-deployment stability of the structure and to establish adequate, but not overly conservative, requirements for active control. For example, characterizing the passive deployment precision of a structure determines the need and requirements for an on-orbit quasi-static active control. Similarly, characterizing the post-deployment stability of a structure establishes the need and defines the requirements for high-bandwidth active control.

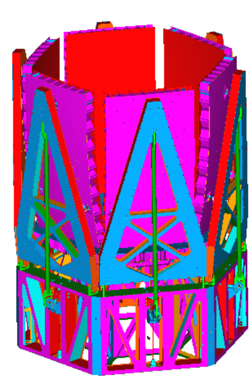
Without a clear understanding of deployment precision and post-deployment stability, it is difficult to establish reasonable requirements for on-orbit active-control systems. Uncertainty in these requirements may lead to increased complexity (and cost) in the development of an on-orbit active-control system. Furthermore, uncertainty in the requirements leads to increased system-development risk because estimates for deployment precision and post-deployment stability requirements that are thought to be conservative might, in fact, neglect effects, such as high-bandwidth microdynamics, that could substantially diminish the performance of the active system. Thus, it is neither conservative nor prudent to presume that all microdynamic responses can be compensated for by active control.

For ultra-large optical systems, the deployed or assembled metering structures will most likely involve at least an order of magnitude increase in the number of mechanical joints compared to the small deployable metering structures currently under study. Consequently, it is expected that microdynamic disturbances in these ultra-large systems will be at even greater levels than currently seen in small systems, and the problem of designing efficient and reliable active control systems will be even more challenging.

Ultra-Large Optical Systems: Where are We Now?

Since 1994, the University of Colorado and NASA Langley Research Center have been jointly conducting a research program to advance the state-of-the-art of high-precision deployable structures. The broad goals of this program have been to enable the design of deployable structures that exhibit sufficient dimensional stability to function as metering structures for optical instruments, and to minimize the complexity and cost of such structures by maximizing passive dimensional precision and minimizing the need for active control.

From this research, design principles for high-precision deployment mechanisms have been derived. For example, it has been shown that, unlike freeplay that can be eliminated by increasing preload in deployment mechanisms, the frictional interactions that give rise to microlurching can be amplified by increasing preload (ref. 12). As a consequence of this and other "lessons learned," new high-precision deployment mechanisms have been developed (e.g., ref. 13), and substantial mechanical-response testing has been performed on these mechanisms (e.g., ref. 14). These new high-precision deployment mechanisms have recently been incorporated in a practical, economical design for a 3-m-class, deployable (non-imaging-class) telescope mirror for application to space-based lidar instruments (ref. 15, Fig. 5), which was co-developed by NASA and Composite Optics, Inc.



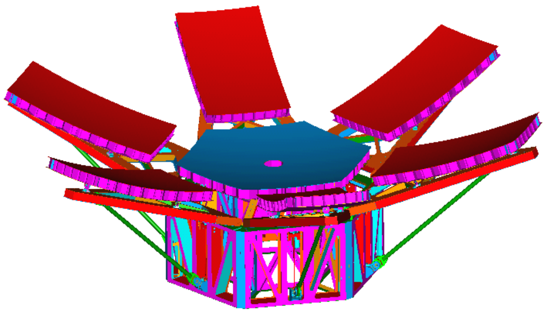


Fig. 5 3-m-class deployable telescope mirror for near-term lidar applications.

The deployable lidar telescope mirror represents a substantial advancement in the state-of-the-art in space-based telescope construction in that it incorporates low-areal-density, composite mirror panels (which have their roots in the LDR program). The deployable metering structure also utilizes low-CTE composite materials, and the entire assembly is designed to exhibit a net CTE less than that of ULE glass (approximately 0.5×10^{-6} /°F). Testing will begin soon on the first developmental model of the deployable lidar telescope mirror, which includes one deployable perimeter panel of the complete mirror assembly (Fig. 6).

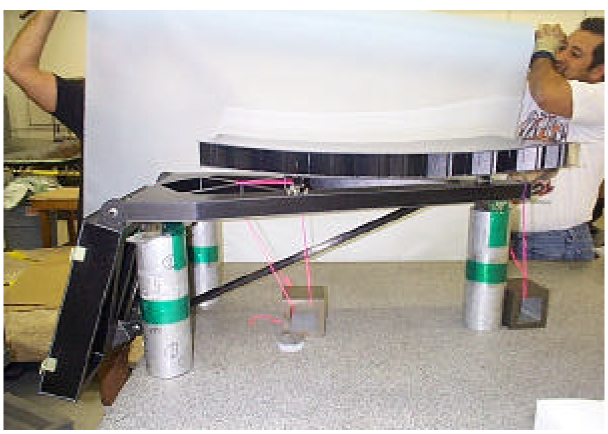


Fig. 6 Deployable telescope mirror test article (testing to begin spring of 1999).

Even though the deployable lidar telescope mirror is a substantial advancement over state-of-the-art, the design is probably the lowest-risk concept imaginable for a deployable telescope. The deployment kinematics are very simple (each deployable perimeter panel simply rotates through about 75° from its stowed to its deployed position), and the metering structure incorporates a minimum number of deployment mechanisms (24 hinges and 6 latches total). So, what does the deployable lidar telescope mirror represent relative to the aggressive, ultra-large optical telescopes envisioned for the future?

In many ways, the deployable lidar telescope mirror is only a small technological step in the right direction toward ultra-large optical telescope systems. The mirror is, by far, the lightest weight, segmented (non-imaging-class) optic developed to date with a net areal density (including metering structure mass) of approximately 15 kg/m^2. Thermally, the deployable lidar telescope mirror should be as stable as the best monolithic mirrors developed to date. Microdynamically, the mirror should be more stable than any other precision deployable structure tested to date. Because of this, it is expected that active alignment control of the reflector panels (if necessary at all) will be accomplished with minimal control-system complexity.

However, despite these dramatic improvements over the present state-of-the-art, the mass efficiency, thermal and microdynamic stability of the deployable lidar telescope mirror are possibly not good enough for ultra-large optical telescope systems. And, it must be remembered that these performance expectations are for a mirror that is only a few meters in diameter, and a metering structure that contains a minimum number of deployment mechanisms. Increasing the aperture diameter by a factor of ten will doubtlessly require substantial continued work. However, as we look to these ultra-large systems, at least we have the advantage of experience gained on smaller systems, and an understanding of the basic nature of the response of these systems.

Finally, although this new-found understanding of the microdynamics of mechanically jointed structures places us in a much better position to consider ultra-large optical systems, it should be remembered that most of what we have learned about microdynamics has come from ground-based testing. To date, very few data have been collected on the microdynamic behavior of mechanically jointed structures in space, and no data have been collected on the on-orbit performance of active control systems to compensate for microdyanmics. Therefore, even the on-orbit performance of the well-developed, deployable lidar telescope mirror remains a question at this point.

To remedy this situation, and begin to build a better understanding of on-orbit microdynamic behavior, the International Space Station (ISS) Program is funding the development of a dedicated, ISS-based microdynamics research facility called the Micron Accuracy Deployment Experiments (MADE) facility (ref. 16). The first launch of MADE is currently planned for 2003, and multiple deployable structures test articles are currently being considered for integration on the first flight. Ultimately, the results of MADE testing should answer many questions that still remain about the microdynamics and active control of large, mechanically jointed, optical metering structures. However, even MADE will be limited to test articles of no more than a few meters in size, so the development of ultra-large optical systems will doubtlessly require a more extensive on-orbit testing capability.

Summary

The desire to build ultra-large optical telescope systems on-orbit is certainly not new to NASA. Many programs in the past have studied various concepts for such systems, and some programs (most recently, the LDR program) have invested a substantial amount of technology-development funding in the interest of making such systems feasible. Unfortunately, despite these investments, no past programs have developed practical concepts for ultra-large telescope systems.

Today, we potentially stand at a technological "turning point" for ultra-large optical telescope systems. For the first time, some of the key engineering design principles that will make practical, mechanically deployable, optically stable structures are understood. These newfound principles are currently being validated in the first generation of deployable optical systems. And although these first systems are diminutive relative to the ultra-large optical systems envisioned for the future, they represent a substantial technological "stepping stone" toward the ultra-large optical systems of the future.

As we prepare to take another look at ultra-large optical systems, the large volume of work that has been accomplished in the past should be considered. In doing so, we must be aware of our recently developed bias in favor of mechanical deployment as a means of constructing large apertures on orbit. For ultra-large apertures, the potential benefits of robotically or manually assembled structures should be investigated. In this analysis, the relative reliability and cost of the various on-orbit construction methods should be reevaluated, and the microdynamic stability and predictability that could be expected from the resulting structures must be compared.

Regardless of the construction technique, there are still substantial technological challenges ahead for ultra-large optical systems, such as on-orbit testing of microdynamics and active control of these systems. But for the first time, it seems that an understanding of the these technology-development challenges exists, as well as the experience to formulate a rational technology-development program that will lead to practical, ultra-large optical systems.

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